METHOD AND SYSTEM FOR AUTOMATIC RAMAN GAIN CONTROL

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CROSS-REFERENCE TO RELATED APPLICATION

This application is related to the co-pending and
commonly-assigned application Ser. No. _____, filed
10   on same date herewith, by Paul Reepschlager, entitled
"Methods and System for Automatic Optical Fiber Type
Identification."

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FIELD OF INVENTION

The present invention relates to fiber optics as well as
to measuring gain in amplified fiber optic spans.
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BACKGROUND OF THE INVENTION

It is known in the art that one manner of obtaining
25   additional optical gain in an amplified fiber optic span
is by pumping the line fiber with high-energy photon (low
wavelength) lasers. In the resulting "Raman effect",
high-energy photons are absorbed by the fiber and may be
re-emitted in the form of stimulated emission in the
30   presence of longer wavelength photons, thus resulting in
amplification. The gain profile for the stimulated re-
transmission has a finite width. Signal gain across a
wide spectral profile may involve the superposition of
gain profiles for several Raman pumps.

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Using adequate pump wavelengths to provide gain across a
signal band, a known model can be derived to predict the
relative pump powers required to achieve a desired gain
profile through pump gain profile superposition, while
5   taking into account several secondary non-linear fiber
optic effects as well.

In the prior art, a closed loop system has been employed
which monitors system span profile parameters for gain
10 derivation. The desired Raman gain is then estimated on
the basis of a modeled solution. However, this
implementation does not take into account the dynamic
nature of the system span profiles. Consequently, in
cases where the system span profiles are dynamic in
15 nature, the known gain control model (algorithm) will
fail. Furthermore, Raman gain estimation on the basis of
a modeled solution often itself employs an open loop gain
implementation, and the resulting gain profile is not
corrected.
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United States Patent 6,081,323 issued to Mahgerefteh et
al. on June 27, 2000, teaches a method and apparatus for
the measurement of Raman gain spectrum in an optical
fiber. This patent, however, describes the determination
25 of Raman gain spectrum and is silent on the measurement
of Raman gain.

Therefore, there is a need for an improved method of
calculating Raman gain which permits dynamic adjustments
30 to system parameters, thus correcting gain inaccuracies
induced by the application of known models and permitting
an accurate derivation of the Raman gain.

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SUMMARY OF INVENTION

Accordingly, it is an object of the invention to provide
a closed loop control strategy using system wavelength
5   profile information to provide accurate derivation of
Raman gain in a fiber optic span.

It is another object of the invention to provide a manner
in which Raman gain may be measured in real-time, in
10   service.

The term "power profile" will be used herein as a generic
term to describe either a gain profile or a loss profile.

15   According to one aspect of the invention, there is
provided a method of dynamically determining a Raman gain
profile of an optically amplified fiber optic span, said
method comprising the steps of: measuring a power profile
for each of a plurality of system components;
20   transmitting the measured power profiles to a central
location; transmitting changes in the measured power
profiles to the central location; and dynamically
calculating the Raman gain profile for the system based
on the changes in the measured power profiles.

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According to another aspect of the invention, there is
provided a system for dynamically determining a Raman
gain profile of an optically amplified fiber optic span,
said system comprising: optical spectrum analyzers for
30   measuring a power profile of said fiber optic span and of
a plurality of system components so as to determine the
existence of a loss or a gain therein; means for
receiving the measured power profiles from the optical
spectrum analyzers, and for receiving changes in the
35   measured power profiles; and means for dynamically

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calculating the Raman gain profile for the system based on the changes in the measured power profiles.

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BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention will be further described with reference to the accompanying drawings, in

10   which:

Figure 1   illustrates diagrammatically a system for
determining Raman gain in accordance with an
embodiment of the present invention;

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Figure 2   illustrates diagrammatically a consideration of
passive losses at the receiving end of a system
according to Figure 1; and

20   Figure 3   illustrates graphically individual pump
wavelength profiles as well as a superposition
of a single pump Raman gain profile in a system
according to Figure 1.

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DETAILED DESCRIPTION OF THE INVENTION

The present invention postulates that, if collected in a
30   central location, mapping information related to
monitored wavelength profiles in a system can be utilized
to derive the Raman gain within a span.

Figure 1 illustrates a system for determining Raman gain
35   in a fiber optic span in accordance with an embodiment of
the present invention. Cost-effective optical spectrum

analyzers (OSAs) 110 are provided in order to monitor
wavelength power profiles, which permits the mapping of
transmit and receive profiles within a fiber optic span
100. If collected at a central location, such as at

5   processor 150, this mapping information may be utilized
to derive the Raman gain within the span. In an
embodiment of the present invention, the processor 150 is
located at the receiving end of the span 100.

10   The following information is necessary in order to
determine the spectral contribution (G3) of Raman pumps
140 incident on the receive amplifier 130: the
originating profile (P1) of up-stream transmit amplifier
120; the loss profile (L2) for fiber optic span 100; and

15   the profile (P4) measured at the input to the receive
amplifier 130. The value of the Raman gain spectral
contribution (G3) may be determined using the following
equation:

20     $P4(\lambda) = P1(\lambda) + G3(\lambda) - L2(\lambda)$, or

       $G3(\lambda) = P4(\lambda) - P1(\lambda) + L2(\lambda)$

Calculation of G3(λ) is preferably performed at the
receiving end. This calculation may be performed

25   automatically by the processor 150, or by any other means
capable of doing so. Alternatively, this calculation may
be performed manually. Advantageously, the result of
this calculation may be displayed on a display means 160.

30   Using this method in accordance with the present
invention, the gain and ripple in the Raman gain profile
will both be directly mapped as opposed to being
estimated through reliance on model equations. The
measurement of an actual spectral profile at the receive

35   amplifier 130 by optical spectrum analyzer 110 permits

pre-compensation of the Raman gain profile to be
implemented and tracked with a high level of confidence.

Some level of inaccuracy may be expected in the derived
Raman Gain profile. This inaccuracy will be manifested
in OSNR (optical signal to noise ratio) results. Thus,
as an outside loop in the control technique, a central
body must be able to dictate Raman gain set-points across
the spans to ensure that the end OSNR results are met.

The determination of the Raman gain using the above
technique will only be effective if the dynamic nature of
the transmit amplifier profile and the loss profile can
be tracked.

First, consider changes in the transmit amplifier
profile, $P1(\lambda)$. To properly map the Raman gain profile,
information about the profile $P1(\lambda)$ of up-stream transmit
amplifier 120 should be fed downstream to the receive
amplifier 130. A continual spectral profile update
strategy, however, may strain usage of an overhead
channel 170. Therefore, in a preferred embodiment, it is
proposed that only status updates be conveyed on a
regular basis from the transmit amplifier. That is, once
complete information about the transmit spectral profile
$P1(\lambda)$ has been conveyed to the receiver amplifier 130,
regular message updates pertaining to the general
operating conditions of the transmit amplifier 120 can
advantageously be sent over the overhead channel 170. A
tolerance band may be defined in the transmit amplifier
profile $P1(\lambda)$, within which minor localized changes in
its output gain and ripple would not warrant a complete
update of its spectral content information to the receive
amplifier 130. Only under changes causing an "event" in
the transmit amplifier's output operating profile would a

complete profile update be sent. An event may be any one
of: a profile change outside of the tolerance band,
wavelength additions, loss of wavelengths, etc.

5   If congestion of the overhead channel momentarily detains
communication of complete spectral updates from the
transmit amplifier, then, in another embodiment, a method
may be put in place to convey only basic information
across the overhead channel (such as wavelength x has
10   been added with power y). Short term reliance on the
open loop Raman amplifier model equations (resident with
the Raman circuit pack) would be permitted to make
limited independent adjustments to the Raman pumps 140 in
order to accommodate transmitted profile changes. Closed
15   loop corrective measures may be implemented when the
complete up-stream information can be conveyed across the
overhead channel.

Next, consider changes in the fiber loss profile, $L2(\lambda)$.
20   Any Raman gain derivation technique that treats the fiber
loss profile as a static entity should cause some
concern. Under such conditions, any degradation to the
passive elements in the system (such as that due to
temperature variations) would result in false estimates
25   of the Raman gain. Therefore, whether the fiber loss
profile is initially procured through measurement
techniques, or estimated based on typical fiber
characteristics, this profile information will need to be
dynamic, being updated periodically based on receive
30   amplifier OSA measurements.

The question remains: how can one determine whether
changes have occurred within the span profile? According
to the invention, the answer lies again in knowledge of
35   conditions in the rest of the span. Input spectral
profile information can be measured at the receive

amplifier 130. If this input profile, P4(λ), changes, but it is known that the booster output profile, P1(λ), has remained consistent, and output power monitor conditions remain unchanged on the Raman pumps 140 (total

5   power as well as individual pump powers), then the changes can be inferred to have occurred along the transmission medium.

Once the measurements of gain and loss profiles have been

10   made, it is necessary to determine the change in the gain or loss profile. Two situations are discussed below: correction of the gain profile during initial system setup; and correction of the loss profile in service, when active parameters have not changed. First, the

15   correction of gain profile during initial system set-up is considered. In initially setting up a span, there must be a preliminary understanding of system parameters in order to determine the amount of Raman gain required. In the present invention, a desired Raman gain profile

20   can be chosen knowing the following values: the output of the transmit amplifier, P1(λ); the desired profile at the receive amplifier input, P4(λ); and an initial condition profile for the span loss, L2(λ). A model is used to set the Raman pump powers to achieve the desired Raman gain

25   profile, and the resulting measured gain will be:

$$G3_{measured}(\lambda) \ = \ P4_{measured}(\lambda) \ - \ P1_{known}(\lambda) \ + \ L2_{initial}(\lambda)$$

This may differ from the desired profile due to model

30   errors for the Raman gain. Hence, initial offset adjustments can be made to the pump powers to achieve:

$$G3_{measured}(\lambda) \ = \ G3_{desired}(\lambda)$$
$$= \ P4_{measured}(\lambda) \ - \ P1_{known}(\lambda) \ + \ L2_{initial}(\lambda)$$

It should be noted that the loss profile is assumed to be correct (due to measurement or due to inferred profile based on typical fiber characteristics). This is a

5   necessary starting point.

Next, consideration is given to the correction of the loss profile in service, when active parameters have not changed. With any intended modification to the Raman

10   gain profile, it must be assumed that the fiber loss profile is correct and static. This implies that, under steady state transmit amplifier and Raman amplifier operating conditions, the loss profile must be monitored and updated accordingly to account for environmental

15   impacts upon it.

A change in the loss profile will be noticed as a change of the profile incident upon the receive amplifier. Under conditions wherein $P1(\lambda)$ has not changed and the Raman

20   pumps are kept at a given operating point, changes in $P4(\lambda)$ may be attributed to a change in the loss of the transmission fiber $L2(\lambda)$. However, a change in $L2(\lambda)$ will result in a change in $G3(\lambda)$ through a change in the effective length of the Distributed Raman amplifier.

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Therefore, before the change in fiber loss:

$$P4(\lambda) = P1(\lambda) + G3(\lambda) - L2(\lambda)$$

30   After the small change Δ in the received power at P4:

$$P4(\lambda) + \Delta(\lambda) = P1(\lambda) + G3(\lambda) - \delta_G(\lambda) - L2(\lambda) - \delta_L(\lambda)$$

Where $\Delta(\lambda) = \delta_G(\lambda) + \delta_L(\lambda)$, and $\delta_G(\lambda)$ is the change in the Raman gain profile and $\delta_L(\lambda)$ is the change in the fiber loss spectrum and is much smaller that $L2(\lambda)$.

5   Since it is very difficult to provide a simple method which (in low computational time) may determine $\delta_G(\lambda)$ and $\delta_L(\lambda)$, a simple linear approximation is used. As an initial supposition, consider $\delta_G(\lambda)$ as being very small compared to $\delta_L(\lambda)$. As such, since the entire change in

10   $P4(\lambda)$ will be attributed to a change in the loss profile, $\delta_L(\lambda)$ can be calculated very easily ($\Delta_{measured}(\lambda) = \delta_L(\lambda)$). If the assumption is made that the change in fiber loss is equally distributed all along the transmission fiber, a change in the loss per unit length ($\Delta\alpha$) can be derived

15   from $\delta_L(\lambda)$.

As a second step in the analysis, it is then desirable to estimate the change in Raman gain occurring from the change in the fiber loss, since (as a counter to the initial supposition) there does exist a finite change to

20   $\delta_G(\lambda)$. In the linear regime, the Raman amplification depends only on three parameters: the Raman gain coefficient (Cr), the pumping power (P) and the absorption per unit length at the pumping wavelength (α).

25   In fact, it can be found that for a particular pump (i):

$$\delta_{G,i} = \frac{-4.343\ C_{r,i}\ P_i\ \Delta\alpha}{\alpha_i^2}$$

30   Cr and P are constants in the present case, α is known from the previous iteration while $\Delta\alpha$ has been estimated previously. For a given signal wavelength, δ_G can then be estimated by adding the contribution from each pump.

The $\delta_L(\lambda)$ parameter can then be re-estimated by subtracting $\delta_G(\lambda)$ from the measured value $\Delta(\lambda)$:

$$L2(\lambda)_{updated} = L2(\lambda)_{previous} + \delta_L(\lambda)$$
$$= L2(\lambda)_{previous} + [\Delta(\lambda) - \delta_G(\lambda)]$$

Since it desirable to maintain a time-invariant profile into the receive amplifier, loss profile updates imply a need for Raman gain profile updates, since the Raman gain profile set-point is a function of the loss profile. Once adjustments to the Raman pump powers have been made to account for changes to the loss profile, the resultant gain profile measurement can be made:

$$G3_{measured}(\lambda) = P4_{measured}(\lambda) - P1_{known}(\lambda) + L2_{updated}(\lambda)$$

and corrective offset adjustments can be applied to the Raman pumps.

Updates to the loss profile and Raman Gain profile may be made regularly in incremental iterative steps.

In calculating the Raman gain, it is important to know if passive losses that may exist at the receiving end (i.e. patch panel loss, filter losses…) factor into the equation. If so, there is the potential for a large unknown offset on the measured gain.

Figure 2 is a modification of the concepts presented in earlier. Here an extra element 200, with a loss profile of C5 has been added to account for the static passive losses that will appear at the receiving end. Two other parameters are considered as well: L2' and P4'. The profile P4, at the input of receive amplifier 130, is

measured after the static losses, C5. The equivalent
profile measurement without static losses is P4'. Since
loss profile measurements, L2, will also be made at the
input to the dual amplifier, the loss due to the fiber

5 alone (without C5) is noted in the diagram as L2'. Raman
gain, G3, needs to be defined as the actual gain derived
by pumping the fiber. Hence, when setting up pump powers
to deliver fiber gain, one should account for the
additional static loss C5 (relatively easy to do with

10 closed loop gain control).

Having defined parameters above, consider how the Raman
gain is derived.

15 $$G3(\lambda) = P4(\lambda) - P1(\lambda) + L2(\lambda)$$

with P4 and L2 measured at the dual amplifier input.

But in this case, $L2(\lambda)=L2'(\lambda)+C5$ and $P4(\lambda)=P4'(\lambda)-C5$

20 Thus:

$$G3(\lambda) = P4'(\lambda) + C5 - P1(\lambda) + L2'(\lambda) - C5$$
$$= P4'(\lambda) - P1(\lambda) + L2'(\lambda)$$

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Therefore, the calculation of G3 using measured
parameters L2 and P4 is insensitive to the static losses
on the receiving side.

30 Measurement of the loss profile can be effected under
start of life, non-traffic-carrying conditions. If the
transmit amplifier pumps are turned up to deliver
superfluous (high power) Amplified Spontaneous Emission
(ASE), this launched ASE profile could first be measured

35 at the amplifier output using the OSA, and then measured

at the receiving dual amplifier input. The difference
between the profiles would be the mapping of the span
loss profile.

5   As a first step, the Raman pump power settings need to be
calculated relative to the fiber loss profile in order to
achieve a specified Raman gain profile. For this reason,
the fiber loss profile needs to be measured (or estimated
by a typical value).

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As a second step, it is useful to determine the Raman
gain spectrum provided by each pump. The combined Raman
flat gain profile is the result of the superposition of
several individual pump wavelength profiles, as

15   illustrated in Figure 3.

It is evident from Figure 3 that the shapes of the pump
profiles must be known to permit an effective
superposition. The shape is empirically determined, and

20   is dependent on fiber type.

A caveat lies in the reliability of using a pre-
determined per-fiber-type typical Raman pump profile when
implementing a solution. This use does not allow for

25   tolerance variations with same-type fibers. One solution
to this problem is accomplished by measuring the pump
profile on-site. Under the same start of life (traffic
free) conditions used in determining the loss profile,
each pump wavelength can be turned up independently, and

30   the resultant profile mapped at the receive amplifier.
The resultant profile is derived through the difference
between the ASE profile incident on the receiver
amplifier before and after the Raman pump power
application. This technique would be particularly

35   valuable in a situation wherein a foreign fiber type has
previously been spliced into a span, and the typical

profile for the dominant fiber type may not be
applicable.

It was mentioned earlier, with respect to the correction
of gain profile during initial system set-up, that during
system initialization, the Raman gain model provides pump
set-points which may be non-optimal due to model
inaccuracies. That is, the resulting gain profile will
be measured through

$$G3_{measured}(\lambda) = P4_{measured}(\lambda) - P1_{known}(\lambda) + L2_{initial}(\lambda)$$

and this measured profile may not match the desired
profile. Pump offsets may be necessary to achieve:

$$G3_{measured}(\lambda) = G3_{desired}(\lambda)$$

Therefore, as a third step in the start of life
initialization procedure, it is possible to provide an
initial estimate of this offset to provide a first order
of correction to the model before traffic is activated
onto the link.

Under the transmitter amplifier ASE condition, if the
Raman pumps were then activated to provide a pre-
determined (modeled) gain, that resultant gain can be
measured at the receive amplifier. This provides a
method for comparing the gain provided by the model
against empirical observation.

Furthermore, if a link budget analysis has dictated that
the Raman gain within a span is to have a value Y, two
other gain values can be measured using the above
procedure, X being a value marginally below the desired
point, and Z being a value marginally above the desired

point. The error between the set-point gain X and
measured results can be obtained. Likewise, the error
between the set-point gain Z and measured results can be
obtained. From interpolation between these error

5   results, a linear function on the expected error in the
gain Y can be found and used to first provide initial
pump offsets on the model, and then for adjustment
purposes.